Atmospheric hazards for entry, descent and landing of future missions to Mars: numerical simulations of fine-scale meteorological phenomena

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In order to allow safe entry descent and landing, as well as mission surface operations, constraints apply to the selection of suitable landing sites. These constraints are defined in terms of general characteristics related to the specific mission profile (interplanetary transfer, waiting orbit injection and orbital waiting period and eclipse mitigation strategies) and to the EDL operations (entry conditions and environment, safe operation of the descent system with parachute deceleration, controlled rockets braking, touchdown with vented airbags). Most constraints are relative to « static » properties such as the geographical location, the altimetry, and the soil thermophysical constants. Few constraints are relative to the « dynamical » properties of the atmosphere, i.e. meteorological variations of density, temperature and winds, notwithstanding these are the most crucial characteristics to predict so as to ensure the success of the EDL phase. Martian mesoscale and microscale meteorological models are one of the relevant tools that can be used to predict the local and regional meteorological variability likely to be encountered at several proposed landing ellipses during Entry, Descent, and Landing. Most of the atmospheric hazards in the Martian lower atmosphere are not evident in current observational data and general circulation model simulations and can only be ascertained through mesoscale modeling of the region. The Laboratoire de Météorologie Dynamique (LMD) Mesoscale Model is a versatile simulator of the Martian atmosphere and environment at horizontal scales ranging from hundreds of kilometers to tens of meters. Specific simulations with relevancy to assessment of atmospheric hazards possibly encountered in Martian landing sites can be carried out with such a tool. The need for accurate and realistic Martian mesoscale modeling remains critical for the design of upcoming missions to Mars (e.g., Mars Science Laboratory, ExoMars).

I. General facts about Martian mesoscale and microscale modeling

Recent missions to Mars yielded unprecedented views of the Red Planet. High-resolution measurements carried out by the instruments onboard Mars Global Surveyor between 1996 and 2006 revealed the diversity of the Martian meteorological phenomena at various horizontal scales below 100 kilometers. More details were eventually provided by the (still ongoing) high-accuracy measurements of the Mars Exploration Rovers, Mars Express orbiter and Mars Reconnaissance Orbiter. Large-scale atmospheric circulation (horizontal scale ~ 100-1000 km) can be simulated by general circulation models (GCM) with coarse grid and simplifying assumptions, such as hydrostaticity. From the early work of the 60s-70s to the recent efforts in the 90s-00s, these tools were crucial to achieve a satisfying understanding of the global climate on Mars [Forget et al., 1999], but were proved unable to adress key questions of local meteorology.

The need for realistic numerical models able to resolve atmospheric dynamics from the meso-scale (100-1 km) to the micro-scale (<1 km, where larger turbulent eddies are computed by the model) is thus critical. The Laboratoire de Météorologie Dynamique (LMD) Mesoscale Model is a new versatile simulator of the Martian atmosphere and environment at horizontal scales ranging from hundreds of kilometers to tens of meters. The model combines the National Centres for Environmental Prediction (NCEP)-National Centre for Atmospheric Research (NCAR) fully compressible nonhydrostatic Advanced Research Weather Research and Forecasting (ARW-WRF) dynamical core, adapted to Mars, with the LMD-GCM comprehensive set of physical parameterizations for the Martian dust, CO_2, water and photochemistry cycles, plus the new sophisticated slope parameterization by Spiga and Forget [2008]. Since LMD-GCM large-scale simulations are also used to drive the mesoscale model at the boundaries of the chosen domain of interest, a high level of downscaling consistency is reached. Definition of correct initialization and boundary conditions was carefully addressed. For instance, in the vertical interpolation process, terrain-following strategy near the surface is combined to pressure-based interpolations at higher altitudes to ensure physical relevance and numerical stability. The LMD mesoscale model was described in Spiga and Forget [2009]. Of particular interest in boundary layer studies is the use of such mesoscale models for so-called Large Eddy Simulations (LES, also referred to as microscale modelling): the grid spacing is lowered to a few tens of metres so as to resolve the larger turbulent eddies, responsible for most of the energy transport within the boundary layer. Martian LES induced a leap forward in understanding the boundary layer dynamics on Mars and allowed the study of fine-scale structure of the Martian daytime boundary layer, dominated by convective processes (the “convective” boundary layer): mixed-layer growth, polygonal cells, thermal updrafts and convective.

Diagnostics from the model were found to be consistent with independent simulations or measurements in a large range of applications, as explained in greater details in Spiga and Forget, 2009. The results of the mesoscale model in coarse resolution mode, with free evolution in the longitudinal dimension, are consistent with the LMD-MGCM calculations for vertical thermal profiles, latitudinal atmospheric structure, and longitudinal tidal wave structure. The model diagnostics of the near-surface pressure, wind, and temperature daily cycles in Chryse Planitia are in accordance with the Viking and Pathfinder measurements. Afternoon gustiness at the respective landing sites is adequately accounted for provided that convective adjustment is turned off in the mesoscale simulations. Through large-eddy simulations in Gusev Crater, the model describes the mixing layer growth during the afternoon, and the associated dynamics: convective motions, overlying gravity waves, and dust devillike vortices. Modelled temperature profiles are in satisfactory agreement with the Miniature Thermal Emission Spectrometer (Mini-TES) measurements. Recent work shows that the Large-Eddy Simulations with the LMD model are also able to capture variations of the BL monitored by Mars Express radio-occultation techniques [Spiga et al., 2010]. Qualitative and quantitative wind predictions in topographically uneven locations such as Valles Marineris, are in good agreement with the previously performed independent mesoscale simulations in the literature: the fact that intense upslope and downslope flows take place along the Valles Marineris rims (reaching respective velocities of 30 m/s and 40 m/s, with a vertical component of 7 m/s) is confirmed by our model, and the influence of the topographical channelling on the winds within the canyon is found to be significant. The water ice clouds controlled by the Tharsis and Olympus Mons topographical obstacles are reasonably reproduced by the model, which predicts consistent altitudes of the afternoon clouds with respect to remote-sensing retrievals. A nighttime warm ring at the base of Olympus Mons was identified in the simulations, resulting from adiabatic warming by the intense downslope winds (up to 40 m/s 120 m above the local surface) along the flanks of the volcano. The surface temperature enhancement reaches +20 K throughout the night this signature is also found in the TES measurements with similar magnitude. Further modelling eventually shows that the phenomenon has adversely affected the thermal inertia derivations in the region.

II. Use of meteorological modeling in EDL phase

A In order to allow safe entry descent and landing, as well as mission surface operations, constraints apply to the selection of suitable landing sites. These constraints are defined in terms of general characteristics related to the specific mission profile (interplanetary transfer, waiting orbit injection and orbital waiting period and eclipse mitigation strategies) and to the EDL operation (entry conditions and environment, safe operation of the descent system with parachute deceleration, controlled rockets braking, touchdown with vented airbags). Most constraints are relative to « static » properties such as the geographical location, the altimetry, and the soil thermophysical constants. Few constraints are relative to the « dynamical » properties of the atmosphere, i.e. meteorological variations of density, temperature and winds, notwithstanding these are the most crucial characteristics to predict so as to ensure the success of the EDL phase. Martian mesoscale and microscale models are one of the relevant tools that can be used to predict the local and regional meteorological variability likely to be encountered at several proposed landing ellipses during Entry, Descent, and Landing. Most of the atmospheric hazards in the Martian lower atmosphere are not evident in current observational data and general circulation model simulations and can only be ascertained through mesoscale modeling of the region.

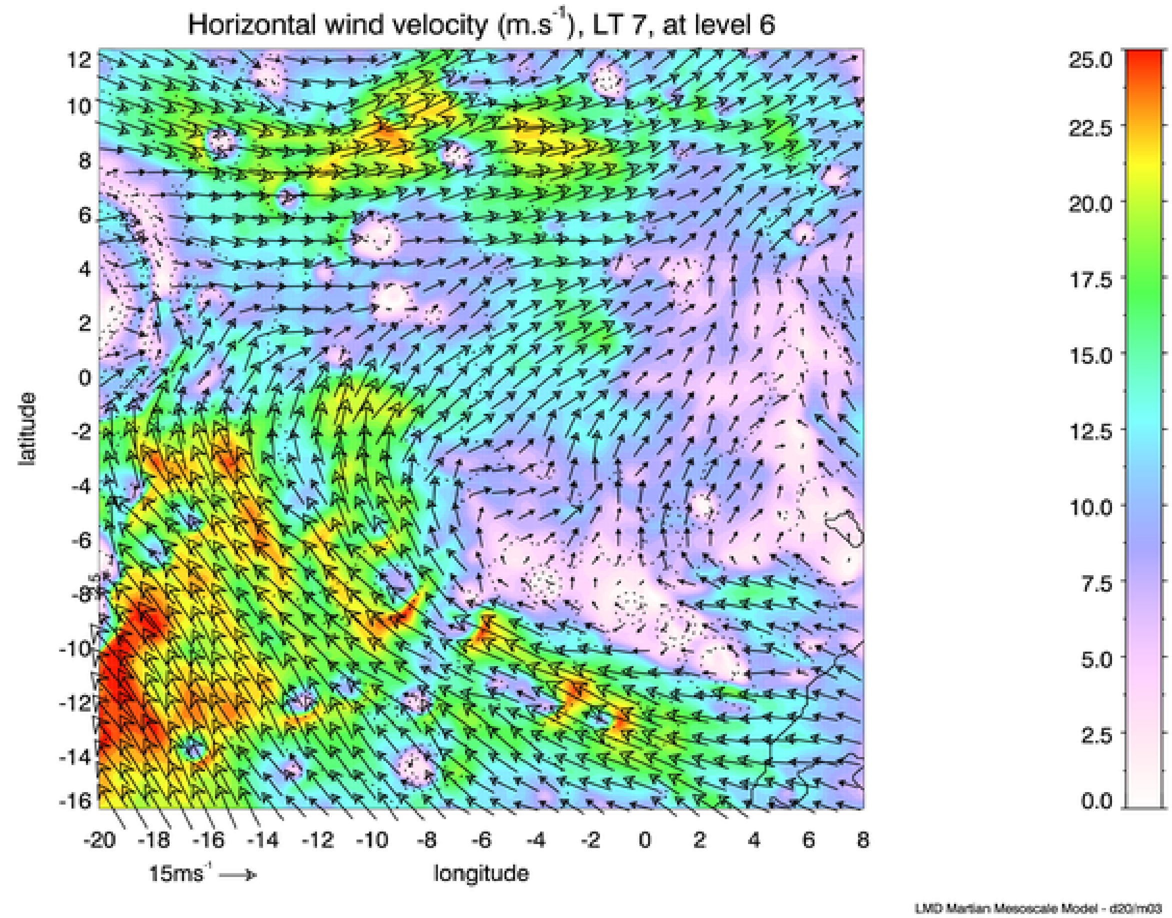

Figure 1 - Horizontal wind speeds and vectors 520m above the Meridiani Terra surface, at local time 07:00. Results from a LMD mesoscale model simulation with 10km horizontal resolution. The model shows how moosoon and western boundary currents (large-scale meteorological circulations) are amplified by the local topography. Areas in red show strong horizontal winds: this information can be used to better constrain ExoMars landing design.

As far as missions to Mars are concerned, mesoscale models have been employed to estimate the atmospheric hazards at the selected landing sites of the Mars Exploration Rovers (MER) [Toigo and Richardson, 2003; Rafkin and Michaels, 2003] and Beagle 2 [Rafkin et al., 2004].They have also provided guidance to design the MER Entry, Descent and Landing system [Kass et al., 2003]. More recently, these models were also used to assess the environmental conditions of the Phoenix EDL and mission [Tyler et al., 2008; Michaels and Rafkin, 2008]. The need for accurate and realistic Martian mesoscale modelling remains critical for the design of upcoming missions to Mars (e.g., Mars Science Laboratory, ExoMars).

For instance, so as to study the EDL phase of ExoMars lander in an Meridiani Terra candidate landing site, LMD Mesoscale Model simulations were run so as to simulate the regional atmospheric motions at 10 km horizontal scales on a chosen domain enclosing the landing ellipse (Figure 1). The inclusion of realistic variations of topography and soil thermal properties at 10s km scales enabled us to investigate the characteristics of anabatic/katabatic winds, gravity waves and other regional-scale phenomena – while the boundary conditions provided the necessary information about the large-scale flow. The atmospheric flow was simulated up to 40 km above the MOLA reference, with 1 km vertical resolution above the boundary layer and refined resolution in the near-surface environment. The simulations allowed to characterize the regional scale winds, with particular emphasis on the wind horizontal and vertical shears, and temperature variability at different levels. It is possible to study the sensitivity of results with local time, season, landing site morphology, dust loading with the model.

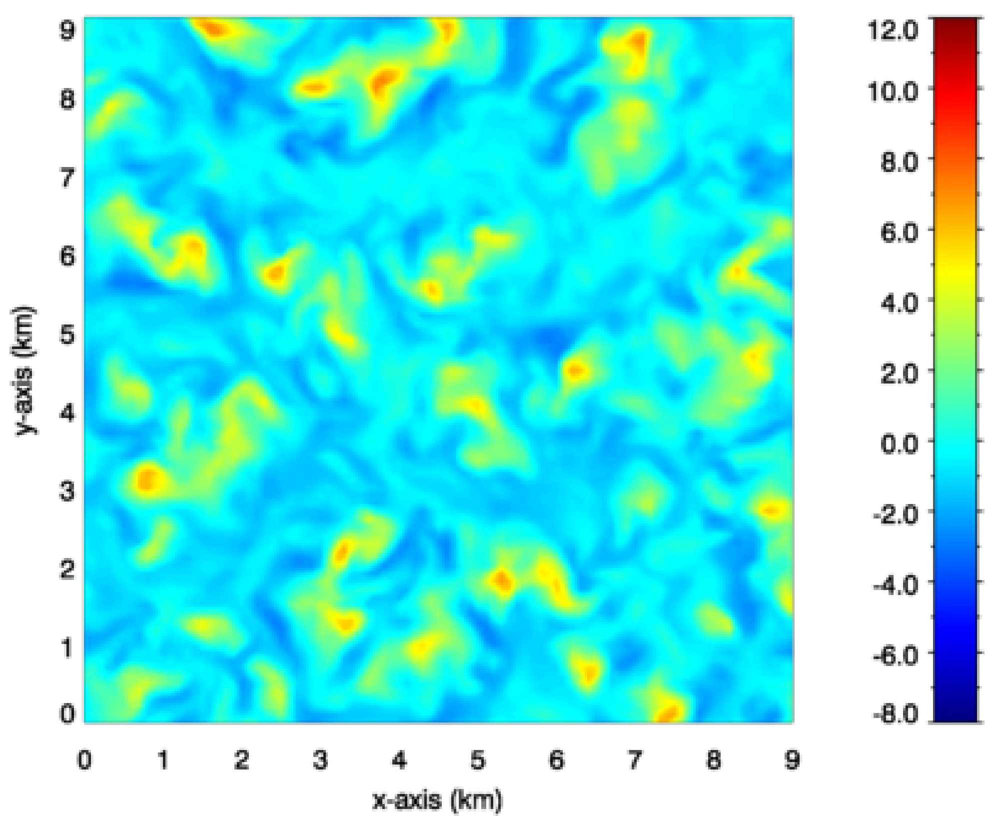

Figure 2 – Vertical wind speed 1km above the Meridiani Terra surface, at local time 11:00. Results from a LMD mesoscale model simulation with 100m horizontal resolution (Large-Eddy Simulations). The model shows updrafts and downdrafts organizing according to a polygonal cellular structure as a result of the boundary layer turbulence. Note that the simulation was carried out without background wind.

In complement to mesoscale simulations, the LMD model can be used to carry out Large-Eddy Simulations to address the question of convection in the Martian boundary layer (Figure 2). Since a relevant concern for the terminal descent phases is related to the vertical wind components, the model must be run at very high horizontal and vertical resolutions in an idealized high-resolution (microscale) mode, in order to evaluate the vertical wind component and the horizontal wind gustiness associated with the boundary layer turbulence. The atmospheric motions is calculated over an infinite flat plane, using periodic boundary conditions (which is the standard procedure in LES). Altimetry, thermal inertia, albedo and dust loading in the atmosphere are set as constants in the simulation domain. The horizontal and vertical resolutions is 100 m with a model top 15 km above the surface. Initial temperature profile in the simulation is extracted from general circulation modeling. Simulations can be carried out with or without background wind. It is then possible to characterize the convective motions in the boundary layer motions (vertical winds + horizontal gustiness + turbulent kinetic energy) over the landing site through LES results. Again, sensitivity of atmospheric circulation and mission hazard with respect to local time, surface properties, dust loading, subgrid-scale roughness can be analyzed. Similarity theory function for vertical velocity variance and vertical eddy heat flux can then be derived from the Large-Eddy Simulations to allow for fast computations of the Martian boundary layer statistics.

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